High-Purcell factor, ultra-small mode volume quasi-H1 photonic crystal defect lasers in InGaAsP membrane

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Abstract: The ultra-small mode volume, high-Q quasi-H1 photonic crystal cavity was demonstrated in InGaAsP membrane. The lasing properties of the cavity were characterized. The operated mode and profile were analyzed with the finite-difference time-domain method.

OCIS codes: (140.5960) Semiconductor lasers; (250.5300) Photonic integrated circuits; (270.5565) Quantum communications

Introduction

Photonic crystal can support a nanocavity with the ultra-high quality factor (Q) value and the ultra-small mode volume (V_m) which has a high Purcell factor environment to study strong atom-photon coupling phenomena. There are demonstrations for the ultra-high Q value [1, 2] and the ultra-small mode volume photonic crystal cavities [3,4]. In this study, we demonstrate an ultra-small mode volume, high-Q photonic crystal lasers in InGaAsP membrane before the cavity is applied for single photon sources with InGaAs quantum dots (QDs) [5]. The designed quasi-H1(qH1) cavity was formed by reducing the hole size of two neighboring air holes at the center of photonic crystal lattices, then the two modified holes were shifted to align the outside edges of the original holes. Fig.1 shows the SEM image of a designed qH1 photonic crystal cavity with the lattice constant (a), original hole radius (r), the modified hole radius (r').

Fabrication

In the fabrication, the qH1 photonic crystal cavities were implemented in a 240nm thick InGaAsP layer on the InP substrate. The InGaAsP layer contents four 10nm thick strained InGaAsP quantum wells (QWs) which is designed for the lasers operated near 1550nm wavelength. A silicon nitride (SiN_x) layer and a polymethylmethacrylate (PMMA) layer are deposited for the dry etching processes and electron beam lithography .The photonic crystal patterns were defined by electron beam lithography on the PMMA layer, followed by two dry etching steps with CHF_3/O_2 mixture and $CH_4/Cl_2/H_2$ mixture gas in the inductive couple plasma (ICP) system. The membrane structure is then formed by selective wet etching with the mixture of HCl and H_2O (4:1) at 0 ^oC. Fig. 1 is a SEM image of a qH1 photonic crystal cavity.

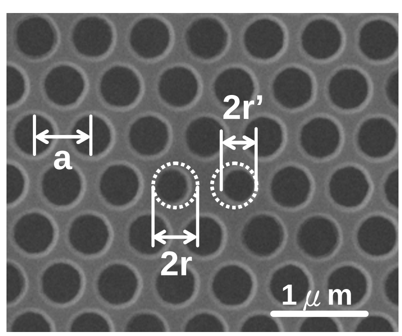


Fig.1 The SEM image of a qH1 photonic crystal cavity with the lattice constant a, original hole radius r, the modified hole radius r'. The two modified holes were shifted to align the outside edges of the original holes.

Measurement and discussion

The photonic crystal cavities were optically-pumped at room temperature by using an 850 nm wavelength diode laser at normal incidence with a 1.5% duty cycle and a 30 ns pulse width. The pumping spot, which is focused by a 100x objective lens, is approximately 1.5 μm in diameter. The output power was collected by a multi-mode fiber connected to an optical spectrum analyzer. Fig. 2 shows the lasing spectrum from a qH1 cavity with lattice constant (a) 620 nm, hole radius (r) to lattice constant (a) ratio 0.33, and the modified hole radius (r') to lattice constant (a) ratio 0.26. The insert figure in Fig. 2 is the light-in light-out curve of this qH1 cavity. The lasing wavelength is 1620.8 nm, and the incident threshold power is only 0.31 mW. The estimated Q value of the qH1 cavity is about 3300 from the resonant spectrum. We also characterized more than 100 cavities with different lattice constants and recorded their lasing wavelengths. The normalized frequency of the observed lasing mode from the cavities is 0.385.

The 3-D finite-difference time-domain (FDTD) method was used to simulate the fabricated cavity. Fig. 3(a) shows the comparison of the simulation and measurement in wavelength. The top gray spectrum was the calculated spectrum from FDTD simulation, and the bottom black spectrum is a measured spectrum with a lasing mode and a resonance mode from a qH1 photonic crystal laser. The band gap of the photonic crystal lattices is from 1521.3 nm to 2019.9 nm which is the shadow region. It indicates the lasing modes here locate inside the photonic band gap region, and the resonance was the band edge mode. A good agreement is obtained between the calculated and measured spectra. The small shift (<2%) in the spectrum is attributed to imperfection of fabrication. Fig. 3(b) shows the calculated H_z profile for this operated mode. The mode volume of this operated mode is less than $0.02\mu m^3 \sim 1.2(\lambda/2n)^3$ from the simulation results. The Q/V_m value is approximately 165000 and the Purcell factor is approximately 1700 which is good for demonstrating a single photon source with QDs.

In short, we demonstrated a qH1 laser cavity with a small mode volume ~ $0.02\mu m^3$ and a high-Q value 3300. This high Purcell factor cavity is able to achieve high efficient lasers and single photon sources.

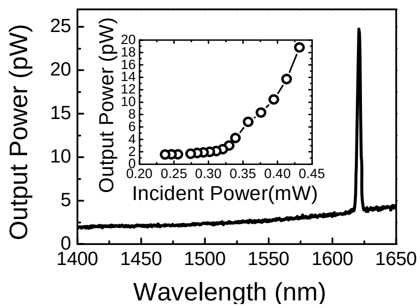
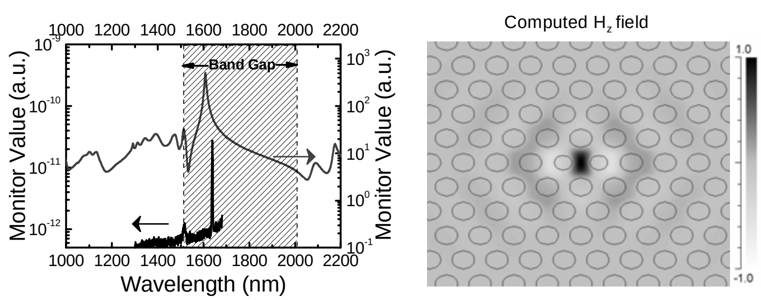


Fig.2 The lasing spectrum of a qH1 cavity with the lasing wavelength 1620.8 nm. The insert figure is the light-in light-out curve, and its incident threshold power is approximately 0.31 mW.



(a) (b)

Fig. 3 (a) The comparison between 3-D FDTD simulation and measured spectrum of a qH1 cavity. Top curve (gray) is simulated spectrum, and the bottom curve (black) is a measured lasing spectrum. The shadow area is the band gap region of the photonic crystal lattices. (b) The calculated mode profiles from the FDTD simulation.

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